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CHARACTERISTICS OF THE 12 GHz, 200 WATT
TRANSMITTER EXPERIMENT PACKAGE FOR CTS
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**PERFORMANCE CHARACTERISTICS OF THE 12 GHz, 200 WATT
TRANSMITTER EXPERIMENT PACKAGE FOR CTS**

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ABSTRACT

Measured performance characteristics from ground tests of the Transmitter Experiment Package (TEP) for the Communications Technology Satellite are presented. The experiment package consists of a 200 W Output Stage Tube (OST) powered by a Power Processing System (PPS). Descriptions of both the PPS and OST are given. The PPS provides the necessary voltages with a measured dc/dc conversion efficiency of 89 percent. The OST, a traveling wave tube with multiple collectors, has a saturated rf output power of 224 W and operates at an overall efficiency exceeding 40 percent over an 85 MHz bandwidth at 12 GHz. OST performance given includes frequency response, saturation characteristics, group delay, AM to FM conversion, intermodulation distortion, and two channel gain suppression. Single and dual channel FM video performance is presented. It was determined that for 12 MHz peak to peak frequency deviation on each channel, dual channel FM television signals can be transmitted through the TEP at 60 W, each channel, with 40 MHz channel spacing (center to center).

INTRODUCTION

The Communications Technology Satellite (CTS) is currently being developed by NASA and the Canadian Department of Communications. The CTS is a high power communications satellite that will make possible the reception of television and two way voice communications using small, low cost ground terminals. Communications links to different parts of Canada and the United States (including Alaska and Hawaii) will be established to support various CTS communications experiments in the areas of education, health and information services. CTS will be launched into synchronous orbit by a Thor Delta 2914 launch vehicle in December 1975. When on station, the spacecraft will be at 116° west longitude, just west of South America.

One of the major responsibilities of the United States in the joint CTS program is to provide a high power Transmitter Experiment Package (TEP). The TEP is used as the final amplifier in the spacecraft SHF transponder (fig. 1). The transponder¹ will receive signals at 14 GHz, translate, amplify and transmit these signals at 12 GHz. Two 85 MHz channels (fig. 2) will be processed through the transponder with one channel amplified to 200 W through the TEP and the other amplified to 20 W by a low power traveling wave tube.

The transmitter experiment package (fig. 3) is made up of two major subassemblies, the Output Stage Tube (OST) and the Power Processing System (PPS). The principal objectives of the TEP development are:

(a) to demonstrate in space an amplifier operating with an efficiency ≥ 40 percent and a saturated rf output power ≥ 180 W at a frequency of 12 GHz,

(b) to demonstrate reliable high-efficiency performance for a transmitter experiment package for 2 years in a space environment, and

(c) to obtain fundamental data for further advancement in the state-of-the-art of high power microwave amplifier operations in space.

This paper presents the dc, rf, and communications performance of the transmitter experiment package as measured during ground testing.

TEP DESCRIPTION

Output Stage Tube

The OST is a linear-beam traveling-wave-tube (TWT) amplifier (fig. 4). It achieves a high level of efficient operation by incorporating two unique design features, a velocity taper of the slow-wave structure² and a 10 plate depressed collector³. The velocity taper resynchronizes the electron beam thereby providing a high level of tube interaction efficiency (28 percent). The 10 plate depressed collector sorts out and reduces the velocities of the spent beam electrons so that they can be collected at near zero kinetic energy thereby reducing the amount of spent beam energy converted into heat. These design features have produced an overall OST efficiency of 48 percent with 224 W of saturated rf output at 12 GHz.

For operation, the OST requires several high voltages. The cathode voltage and current are 11.2 KV at 77 ma. The 10 collector voltages step down from the 10th collector to the second in 10 percent increments of the cathode voltage. The first collector is tied to the power supply. The load on each collector supply varies as a function of rf drive. Two ion pumps on the OST require a voltage of 3.2 KV. The cathode heater requires a low voltage supply that operates at the cathode potential. An anode used to accelerate cathode electrons requires a 250 V potential.

In the complete TEP (fig. 3), the OST is physically mounted onto the PPS with a variable conductance heat pipe system to carry the heat away from the base of the tube to a radiating surface. The TEP is so situated on the spacecraft as to permit the collector cover to radiate directly to space. Four thermistors mounted on the OST are used as temperature sensors. Two diode detectors in the OST output circuit are used to monitor incident and reflected rf power. The TEP signal conditions all TEP sensors for spacecraft telemetry. Instrumentation has been incorporated into the TEP to permit determination of the OST performance.

Power Processing System (PPS)

The function of the power processor is to convert power drawn from the solar array into the forms required by the various system elements. In addition to providing regulated voltages to the output stage tube. The power processor also provides the instrumentation, command, and protection functions for the total system.

Design Features. - In addition to the more conventional considerations, the design of the PPS had to address certain stringent constraints; in particular, the requirement of low output ripple concurrent with a requirement of low stored energy, which serves to prevent damage due to shorts internal to the OST. These requirements were met by the incorporation of several novel techniques.

The input regulator operates in a constant current mode with excess energy being returned to the input bus. This minimizes the effects of inrush current charging the stray capacitances of the transformer

PPS regulation is of the two loop type which controls both the output voltage level, and the input current on a cycle to cycle basis. This scheme not only gives excellent regulation but also keeps all transients under control thus enhancing semi-conductor reliability. The output filter consists of RC networks followed by an active filter which provides the low ripple power without exceeding the stored energy specification. Automatic protection is provided to prevent damage to the OST due to excess body current or high internal pressure. Automatic protection also prevents damage to the PPS due to undervoltage or excess transformer current.

The PPS input and output requirements are listed in Tables I and II while such details as; the considerations of energy storage, power processor turn on times, and the "fail safe" modes dictated by system design are shown in Table III. A simplified block diagram of the power processor is shown in Fig. 5. Most of the power is drawn from the 76 V solar array. The 28 V battery bus powers the cathode heater supply and the ion pump supply allowing for their operation during eclipse conditions.

Physical Characteristics. - The PPS (fig. 3) is contained in a 13 KG (28 lb) package having the dimensions of 24 cm (9.5 in.) wide, 18 cm (7 in.)

tall, and 50 cm (20 in.) long. Considerable attention was given to the detail design of the high voltage section. Transient protection was provided to prevent damage due to arcing. Voltage gradients were controlled between both the components, and the boards themselves. The high voltage section is completely isolated from the low voltage section both physically and electrically. All high voltage terminations have corona spheres attached. Typical of the care given to details is the use of cap nuts to prevent sharp thread edges projecting into the package. Attention to such details is required in order to provide reliable operation of high voltage circuitry. More detailed information on design is given in Ref. 4.

PERFORMANCE CHARACTERISTICS

TEP DC and RF Performance

To simulate a space environment, the flight TEP was tested in a thermal/vacuum facility. TEP temperatures were cycled from the spacecraft control levels to those that will be experienced during eclipse periods. Table IV and the associated figures provide a summary review of the TEP dc and rf performance levels.

The effect of the high level of TEP efficiency can best be appreciated by comparing the raw power required by the CTS TEP to one having a tube without a multiple depressed collector. To produce the same 224 W of rf output, a TEP without the multistage collector would require 955 W of raw dc power as compared to 524 W with the multiple collectors. This increase in raw dc power would increase the size and weight of the spacecraft and the launch vehicle requirements.

The TEP saturated response (fig. 6) shows that with the input power held constant at 23 dBm the output power is maintained above 200 W across the 85 MHz band. The small signal response (fig. 7) shows a peak to peak gain variation of 3 dB across the band. Below the saturation -3 dB level, the power transfer curve (fig. 8) shows a gain variation of 1.5 dB. The group delay response (fig. 9) has no severe second derivative variations that would cause distortion to phase sensitive signals such as color video.

In the two carrier gain suppression tests (fig. 10) each curve begins with only carrier 1 establishing the OST output power. As carrier 2 drive power is increased to a saturation drive level, carrier 1 output power is suppressed. The 224 W curve shows a 4 dB suppression and the 100 W curve 6 dB. Therefore, using the 100 W curve as an example, if a second channel signal were processed through the TEP, and its input level were adequate to saturate the tube, the first channel's output power would be suppressed to 25 W by the second channel. In the 10 W curve there is a 2.5 dB gain expansion of carrier 1 output before a 1 dB suppression. The gain expansion is due to the power transfer characteristic of the TEP that shows an increase in gain from output levels below 40 dB to levels between 40 and 45 dBm.

The third-order intermodulation data reflects low intermodulation distortion when multiple signals are processed through the TEP.

TEP Communications Performance

The transmitter experiment package was subjected to a series of ground tests to evaluate its communications performance. Test results presented are AM to FM conversion and single and dual channel frequency modulated video.

AM to FM Conversion. - Because the time delay of the TWT is dependent upon the amplitude of the input signal, any amplitude modulation present at the tube input results in a phase modulation at the output. In FM or PM transmissions, this added phase modulation appears as an unwanted signal at the receiver output. Tests on the flight model TWT (S/N 2022) produce the results shown in Table V. These measured values of AM to FM conversion are typical of traveling wave tubes.

Frequency Modulated Video Tests. - A complete series of single and dual channel video tests were performed on a transmitter experiment package containing a flight back-up tube (2025). Although these results were obtained using the flight back-up tube, the results are representative of this family of tubes.

Single Channel Video Tests. - Standard video test signals and color program material were used to evaluate the ability of the transmitter to amplify frequency modulated television signals.

Carrier frequency	variable
Peak to peak frequency (white to sync peak)	12 MHz, 18 MHz
Audio subcarrier	7.5 MHz
Audio modulation	None
Received carrier to noise	26 dB
Video monitors	Professional quality, viewed with reduced ambient lighting.
Modulation type	Variable, with pre- and de-emphasis.

Results of the tests are in Table VI

The measured signal to noise ratios agree, within one decibel, with the expected signal to noise values based upon the received carrier to noise ratio and the FM improvement factors for the two different deviations. The transmitter/receiver pair used for the tests had differential phase of 1.5° and differential gain of 5 percent. Thus, the transmitter tube adds almost no differential phase and gain to the system. Subjective quality of the received pictures was excellent, with regard to both noise and color quality.

Two Channel Video Tests. - Tests were performed to determine the conditions under which the transmitter tube can amplify two frequency modulated television signals simultaneously with acceptable interferences. It can be shown that when two information bearing carriers are amplified by a non-linear device, no intermodulation products will fall into either channel if the two center frequencies are separated by twice the channel bandwidth. Also, from two carrier intermodulation tests, it had been found that the maximum power out of each of two carriers in a traveling wave tube was about one-third the saturated power available with a single carrier. Thus, it was expected that with appropriate channel separation, two video modulated signals could be amplified simultaneously by the CTS transmitter experiment package to a level of 60 to 70 W each, and then received with no interference. The test conditions were as for the single channel video tests, but with two channels applied simultaneously. The synchronizing frequencies of the two video signals were not locked in order to provide a more severe interference test. The tests are given in Table VII.

At 12 MHz peak to peak frequency deviation, for 30 MHz difference in carrier frequencies, there was slight interference visible in channel 1 at saturated output for color bar test signals. These signals are a worst case test because of the large uniform color areas where interference is easily noticed and because of a flicker effect in the saturated colors due to the difference of the color subcarrier frequencies. For the same conditions, (12 MHz deviation, 30 MHz spacing), but with program material on both channels, no interference was visible. When the spacing was increased to 40 MHz, no interference was visible even with test signals. The receivers used for the tests had 30 MHz bandwidth IF filters. The spectrums for 30 and 40 MHz spacing are shown in Fig. 11. Note that for 30 MHz spacing, the intermodulation products are immediately adjacent to the signal spectrums, are partially accepted by the receiver filters, and consequently produce interference. The consistently less interference in channel 2 than in channel 1 is due to higher intermod products generated adjacent to channel 1. The rf power out in channel 2 is high than that in channel 1 due to the frequency dependent saturation characteristics of the OST. From these tests, it is concluded that with 12 MHz peak frequency deviation on each channel, 40 MHz channel spacing (center to center) results in no interference when dual channel frequency modulation television signals are transmitted through the TEP at about 60 W, each channel.

Similarly, the tests with 18 MHz peak to peak deviation show interference at the smaller channel separations, and no interference at the greater separations. Spectrums for 40 and 50 MHz separations are shown in Fig. 12. For 18 MHz peak to peak frequency deviation on each channel, 50 MHz channel spacing is adequate to allow dual channel frequency modulation television signals to be transmitted through the TEP at more than 50 W output per channel.

CONCLUDING REMARKS

In a series of ground tests the transmitter experiment package for the CTS was measured to operate with an overall efficiency of 43 percent (48 percent tube efficiency and 89 percent power processing system efficiency). The saturated output power was 224 W at 12.080 GHz. Gain flatness across an 85 MHz band (3 dB peak to peak) and the linearity (1.5 dB maximum deviation from a straight line) were measured. Phase variation was 2 nanoseconds peak. Measured third order intermodulation levels allow multichannel operation below saturation. AM to PM conversion ranged from 4 to 8°/dB depending on frequency and drive.

Tests with video modulated signals showed that the transmitter experiment package adds virtually no differential phase or differential gain. Dual channel video tests indicated that two video signals could simultaneously be amplified by the transmitter to levels of about 60 W per channel with 12 MHz peak frequency deviation and 40 MHz spacing, with no noticeable interference between the received signals. Similarly, no interference was perceptible with each channel deviated 18 MHz peak, and 50 MHz spacing between channel center frequencies.

The development of this high efficiency, high power, transmitter experiment package makes available to the spacecraft designer and the system planner an output amplifier that can effectively use a portion of the 11.7 to 12.2 GHz band allocated for space-to-earth broadcasting. The high efficiency enables use with a spacecraft power system of only 55 percent of the capacity of that required by amplifiers of conventional efficiencies. The high power at 12 GHz, coupled with the achievable spacecraft antenna gain, allows high effective isotropic radiated power levels that can be received by low-cost receiving systems on earth.

REFERENCES

1. L. D. Braun and M. V. O'Donovan, "Characteristics of a Communications Satellite Transponder," Microwave Journal, vol. 17, pp. 45-47, Dec. 1974.
2. H. G. Kosmahl, G. McNary, and O. Sauseng, "High-Efficiency, 200 Watt, 12-Gigahertz Traveling Wave Tube," NASA TN D-7709, June 1974.
3. H. G. Kosmahl, "A Novel Axisymmetric Electrostatic Collector for Linear Beam Microwave Tubes," NASA TN D-6093, Feb. 1971.
4. B. F. Farber, A. D. Schoenfeld, and P. A. Thollot, "Power Processing System for a 200 W Communication Satellite Transmitter," presented at IEE International Conference on Satellite Communication Systems Technology, London, England, April 1975.

TABLE I. - PPS INPUT REQUIREMENTS

Input power	Main bus: 300 W nominal at 76 ± 11 VDC Secondary bus: 30 W nominal at 27.5 VDC ± 3 percent
Commands	20 Commands with interlocking for: turn on/off, control sequencing, and override of automatic protection

TABLE II. - PPS OUTPUT REQUIREMENTS

Cathode heater	Voltage - 4.2 VDC (-11.2 KV to ground)
Cathode/collector supply (cathode)	Voltage - 11.2 KVDC Regulation - ±1 percent Ripple - 0.01 percent P.P.
Cathode/collector supply (collectors)	Voltage - Collector 1 OVDC collector 10 - 11.2 KVDC (remaining collectors in proportion to collector 10 voltage) Regulation - ±3 percent Ripple - 2 percent P.P.
Anode supply	Voltage - 350 VDC (nominal) Regulation - ±1 percent
Ion pump supply	Voltage - 3.2 KVDC Regulation - ±10 percent
Telemetry	32 channels of telemetry, signal conditioned to 0 to 5 VDC

TABLE III. - ELECTRICAL PERFORMANCE

Efficiency	89 percent under nominal conditions
EMI	MIL STD 461 A, notice 3
Protection	Automatic turn-off for (a) low input voltage (b) excess body current (c) excess OST internal pressure
Energy limiting during arc	Less than 1 joule
Current limiting	Protected for any combination of output short circuit conditions
Turn on time	Stable output in less than 40 ms

TABLE IV. - TEP PERFORMANCE SUMMARY

OST Overall efficiency (DC-RF)	48 percent
PPS Efficiency (DC-DC)	89 percent
TEP Efficiency (RAW DC-RF)	43 percent
OST Power Consumption	468 W
PPS Power Consumption	56 W
Saturated RF output power	224 W (fig. 6)
Saturated gain variation (P-P)	0.8 dB (fig. 6)
Small signal gain	34 dB (fig. 7)
Saturated gain	30 dB (fig. 8)
Group delay variation	2 nano-sec (fig. 9)
Noise figure	36 dB
Gain suppression	6 dB (fig. 10)
Two carrier - Sat.	10 dB
Third-order - Sat. -5 dB	14 dB
Intermod ratio - Sat. -10 dB	23 dB
- Sat. -15 dB	35 dB

TABLE V. - AM/PM CONVERSION FOR TUBE 2022

Output level	Frequency (GHz)		
	12.050	12.080	12.110
Saturation	4.8°/dB	6.3°/dB	4.8°/dB
Saturation -3dB	6.0°/dB	5.5°/dB	8.0°/dB
Saturation -5dB	3.6°/dB	5.7°/dB	6.7°/dB

TABLE VI. - RESULTS OF SINGLE CHANNEL VIDEO TESTS
(TUBE 2025, AT SATURATION)

Frequency, GHz	Frequency deviation, MHz	Signal to noise*, dB	Differential phase, deg	Differential gain, percent
12.070	12	43	1.5	2
12.050	18	48	3	5

*Signal to noise = peak to peak picture (white-blanking)
rms noise in 4.2 MHz.

TABLE VII. - DUAL CHANNEL VIDEO TEST RESULTS (TUBE 2025)

Frequency deviation, MHz	Center frequency separation, MHz	Input level drive	RF Power Out, W		Test picture Ch 1 Ch 2	Subjective evaluation of interference Ch 1 Ch 2	
			Ch 1	Ch 2		Ch 1	Ch 2
12 ↓	30 ↓	Sat.	64	80	program/program color bars ↓ ↓	None visible	
		Sat.	64	80		Slight	None
		Sat. + 3 dB	64	64		Slight	None
		Sat. + 6 dB	40	40		loss of sync	slight
↓	40 ↓	Sat.	64	71	↓ ↓	None visible	
		Sat. + 3 dB	64	64			
		Sat. + 5.7 dB	32	32			
18 ↓	40 ↓	Sat.	57	90	program/program color bars ↓ ↓	None visible	
		Sat.	57	90		Slight	None
		Sat. + 3 dB	51	90		Slight	None
		Sat. + 6 dB	20	40		Annoying	Slight
↓	50 ↓	Sat.	51	90	↓ ↓	None visible	
		Sat. + 3 dB	51	80		None visible	
		Sat. + 6 dB	20	51		Slight	None

Channel 2 at 12.100 GHz, Channel 1 at 12.070, 12.060, or 12.050 GHz.

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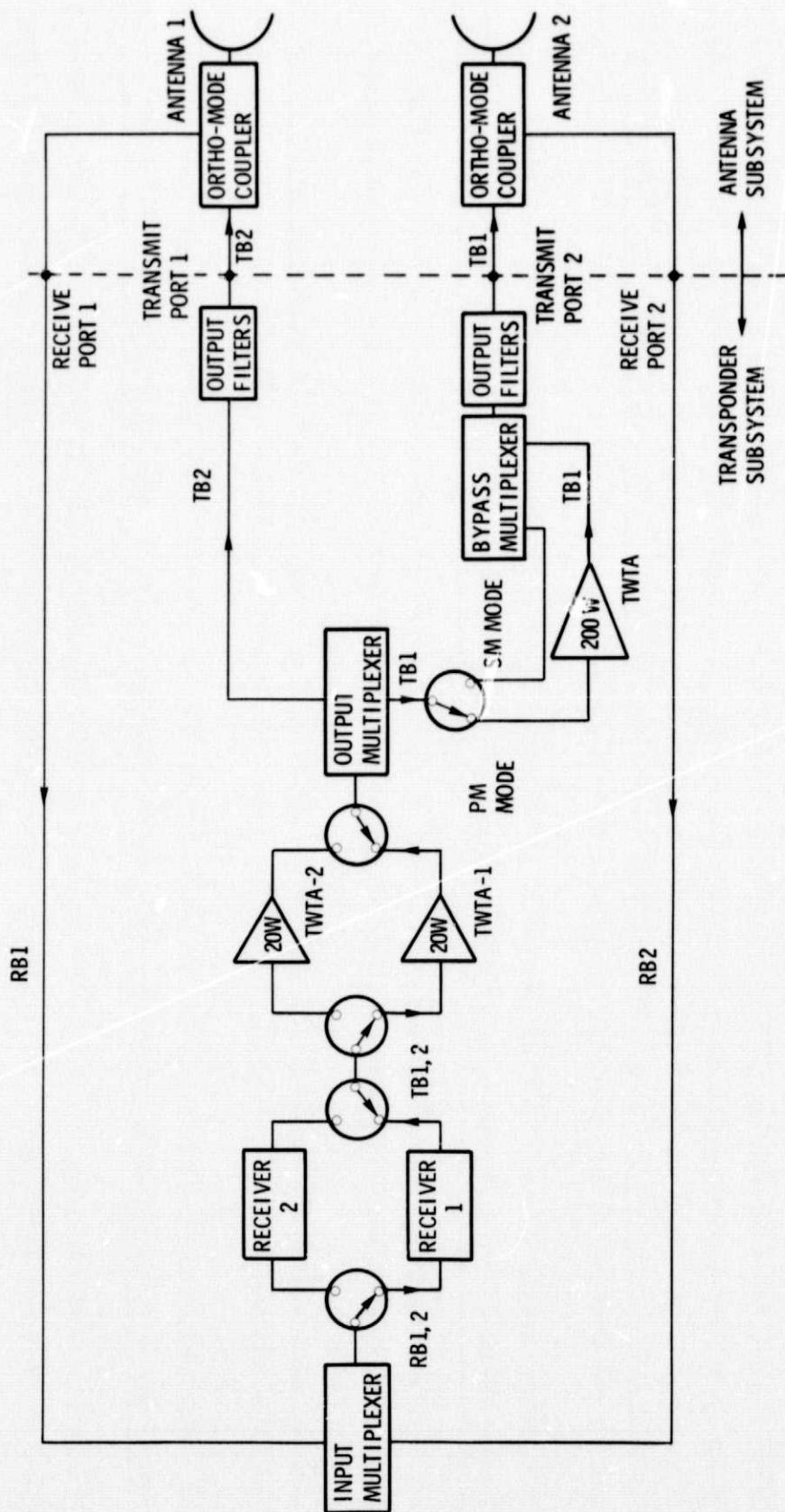


Figure 1. - CTS 14/12 GHz communications transponder.

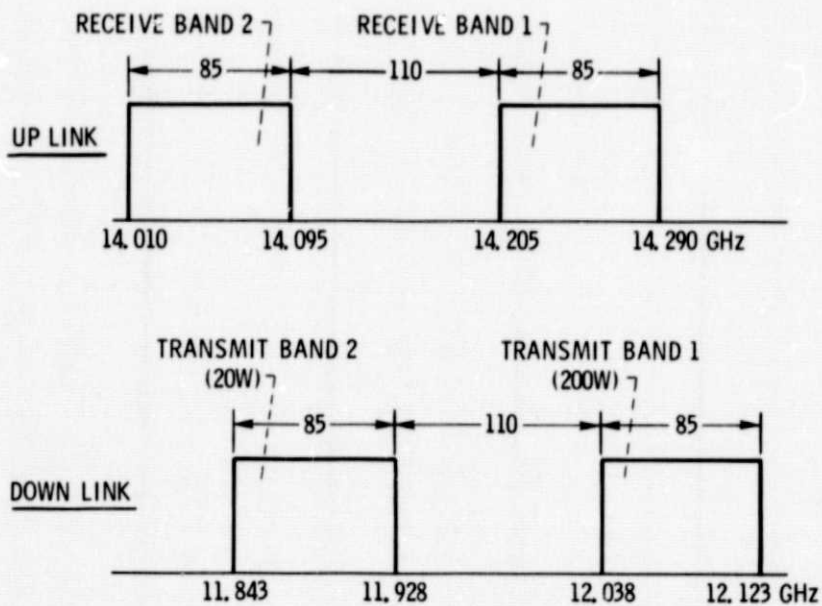
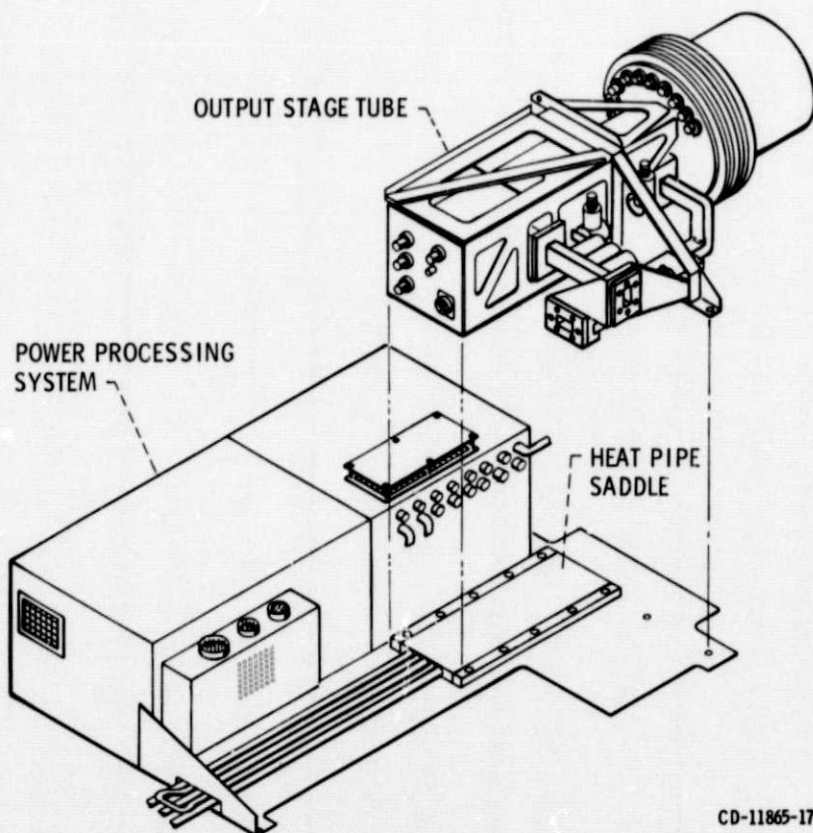


Figure 2. - Communications technology satellite frequency plan.



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Figure 3. - Configuration of transmitter experiment package.

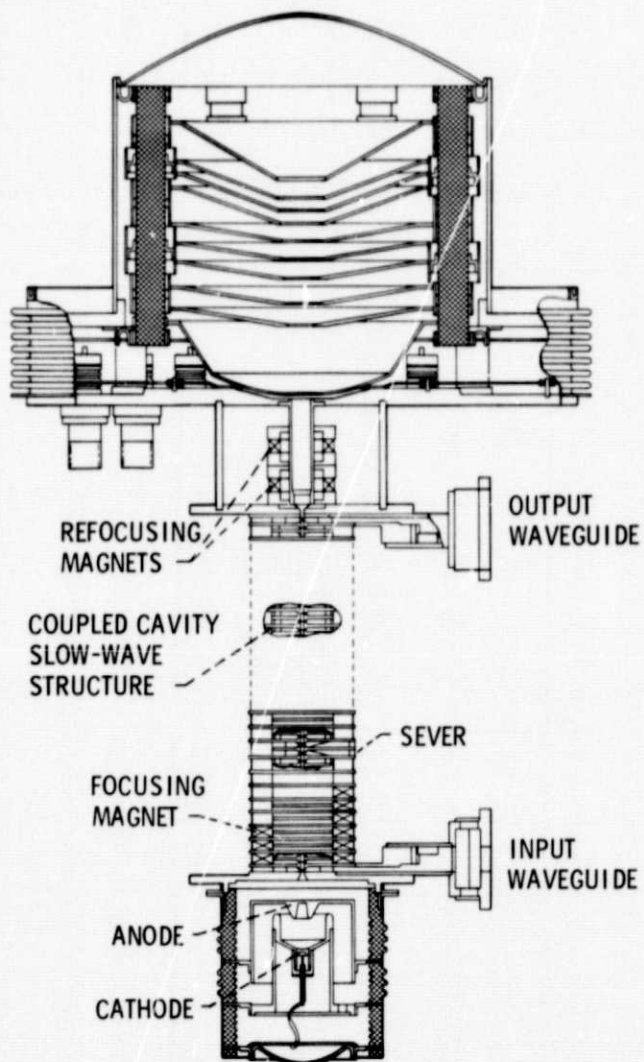


Figure 4. - Coupled cavity traveling wave tube with multistage depressor collector.

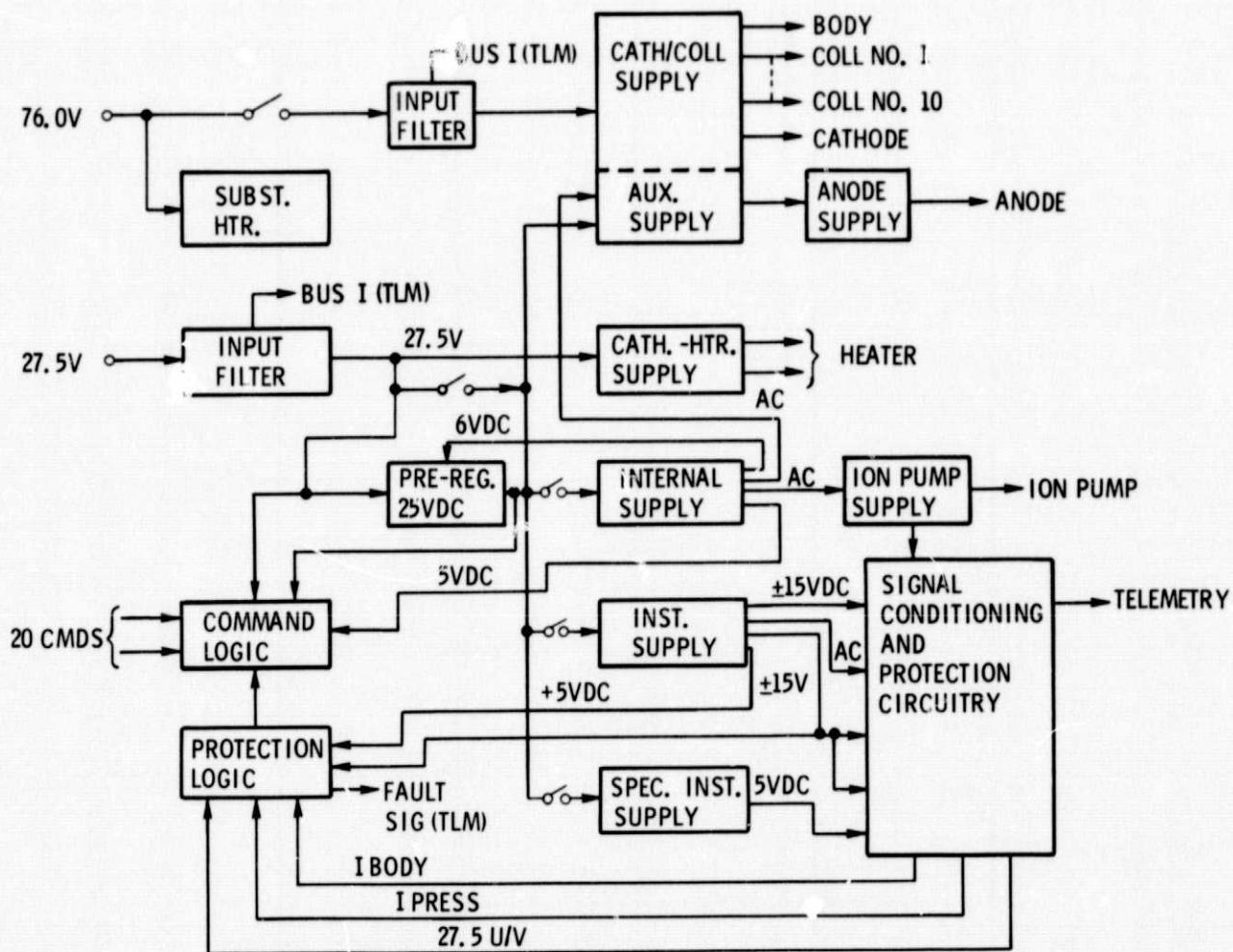


Figure 5. - PPS simplified block diagram.

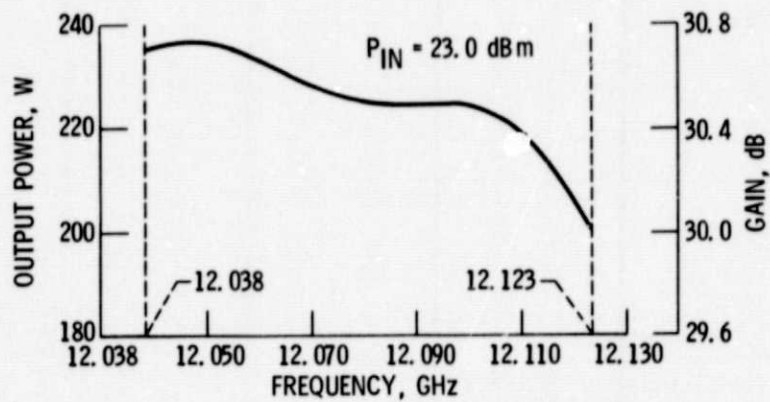


Figure 6. - TEP saturated response.

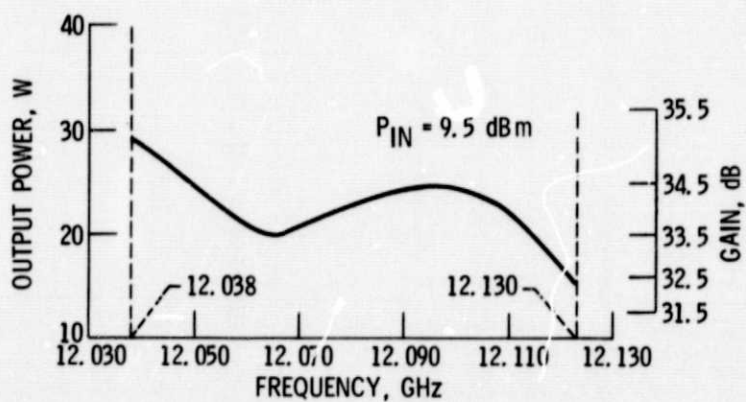


Figure 7. - TEP small signal response.

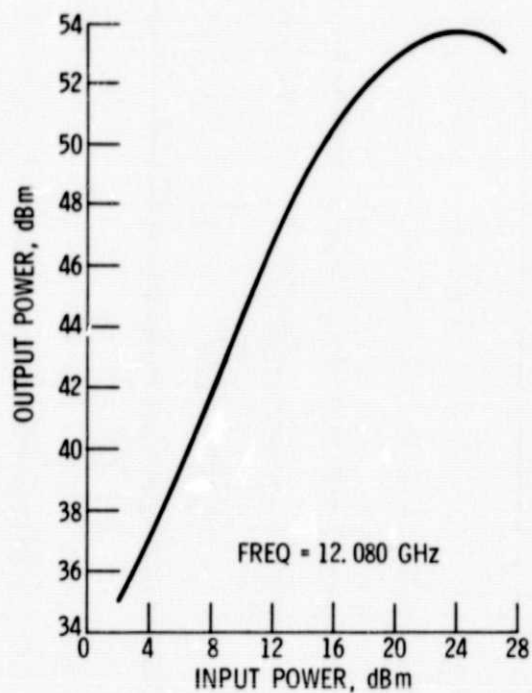


Figure 8. - TEP power transfer.

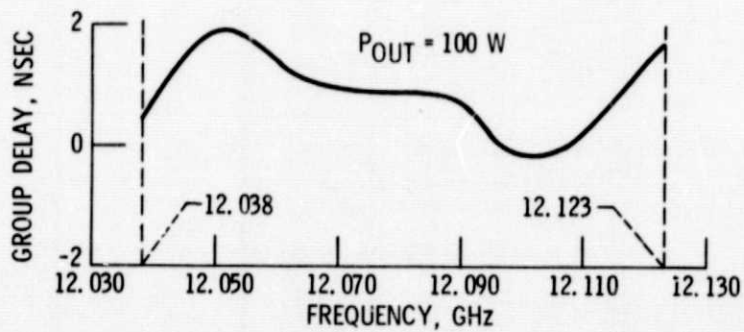


Figure 9. - TEP group delay.

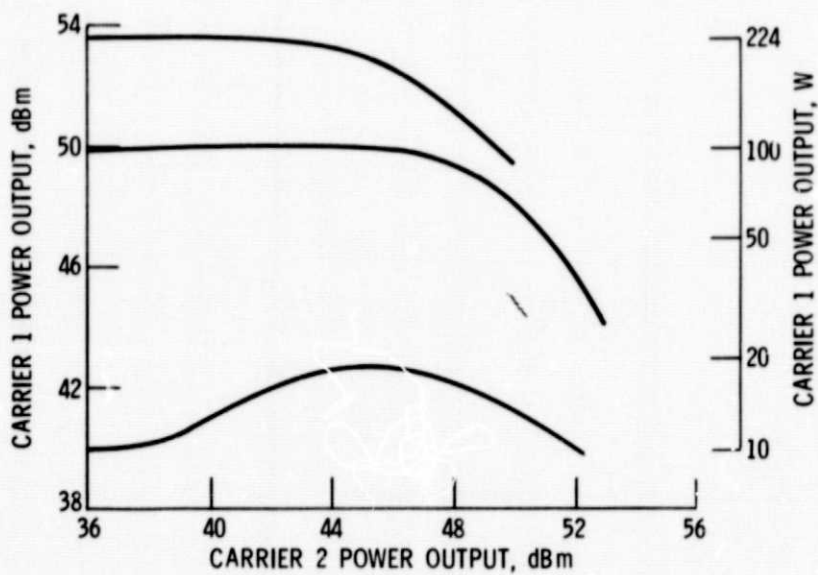


Figure 10. - TEP gain suppression.

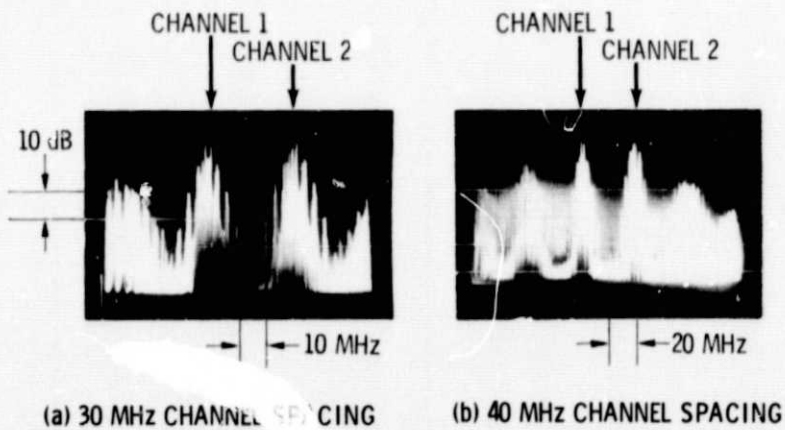


Figure 11. - Output spectra for 12 MHz deviation, dual channel FM video signals.

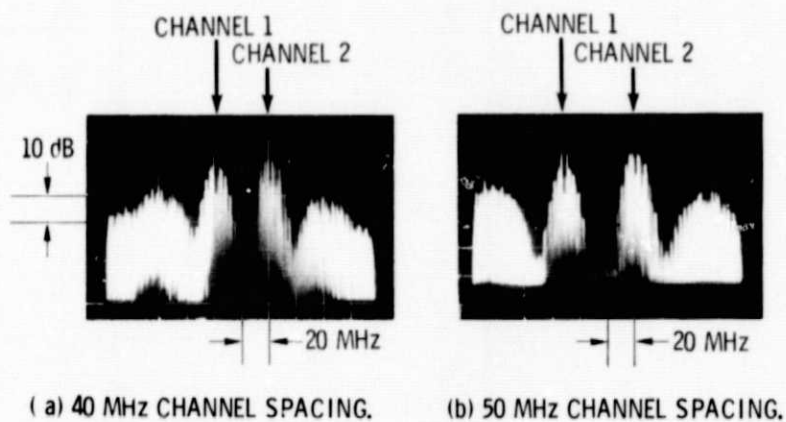


Figure 12. - Output spectra for 18 MHz deviation, dual channel FM video signals.